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Transitioning to high efficiency air conditioning in Saudi Arabia: A benefit cost analysis for residential buildings

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ABSTRACT

This paper assesses the benefits of transitioning to high efficiency air conditioning (AC) equipment for existing units specific to the residential building stock in the Kingdom of Saudi Arabia (KSA). The analysis is based on a calibrated residential building stock model for Saudi Arabia supported by national statistics regarding the characteristics of AC systems. Various housing prototypes, vintages, and locations are included in the analysis. Specifically, the analysis considers the scaling up of the government's High Efficiency AC (HEAC) program which offers 900 Saudi Riyals (240 USD) per unit to consumers for up to 6 split system units with an energy efficiency rating (EER) of 13.0 or more per household. The main findings of the study suggest that upgrading the existing old stock of window units and split systems currently in place to the requirements of HEAC program would generate a reduction in electricity consumption of around 33 TWh/year and 24 million tons of CO_2. Due to the effect of the HEAC consumer subsidy, purchasing a high efficiency unit has a simple payback period for the consumer of 5 years which is faster than less efficient AC options. This would come at a cost to the government of approximately 6 Billion USD resulting in an annual income of 3.0 Billion USD from the sale of avoided fuel associated with the saved electricity consumption.

1. Introduction

Space cooling is the fastest growing energy end-use for building sector and has tripled between 1990 and 2016 worldwide [1]. It is estimated that there are currently over 6 billion air conditioning (AC) units in operation throughout the world with over half used in China and US. On annual basis, 135 million AC units are sold to cool buildings and over 2000 TWh/year of electricity is consumed due to the operation of AC systems [1].

The Kingdom of Saudi Arabia (KSA) characterized by very hot summers and the highest share of AC in household electricity consumption in the world [2]. The use of air conditioning equipment has become prevalent to maintain acceptable thermal comfort within all buildings with a 100% AC penetration rate [3]. Thus, significant increase in electricity consumption as well as peak demand occurs during summer months compared to the winter months. Howarth et al. [4] assessed the relationship between temperature variation, electricity generation, and AC use for KSA. For example, electricity generation reached 60 GW during 2015 summer days due to AC loads but was only 23 GW during 2015 winter days. As the country moves from winter to summer, each 1 °C of temperature increase is found to require 1.18 GW of additional electricity generation. Similarly, Krarti et al. [5] have shown that KSA hourly electricity consumption follows closely outdoor ambient temperatures. In particular, the analysis highlighted the contribution of air-conditioning during summer months when electrical energy demands increase to levels that are double those observed during winter months. Most of the KSA air conditioning loads are attributed to the residential building stock. Indeed, electricity consumed by housing stock represents 45% of the total KSA consumption during 2018 well above that used by the industrial sector (18%), commercial buildings (17%), and governmental facilities (15%) based on reported data [6]. Moreover, over 65% of the 2018 electricity consumed by the residential building stock is due to air conditioning equipment [7].

Several analyses reported in the literature have evaluated a wide range of measures to reduce energy consumption associated with air conditioning for both new and existing KSA residential buildings. Specifically, replacing the existing stock of inefficient window units with more efficient split systems through a 'cash for clunkers' program and phasing out new sales of window units has been identified as one of the highest impactful energy efficiency programs [4]. Moreover, the addition of thermal insulation for walls and roof as well as the installation of

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Nomenclature

AC	Air Conditioning
CO_2	Carbon Dioxide
DX	Direct Expansion
EER	Energy Efficiency Ratio
HEAC	High Efficiency Air Conditioners
KSA	Kingdom of Saudi Arabia
MEPS	Minimum Energy Performance Standard
SAR	Saudi Arabia Riyal
SASO	Saudi Arabia Standard Organization
SEC	Saudi Electricity Company
SEEC	Saudi Energy Efficiency Center
SEEP	Saudi Energy Efficiency Program
USD:	US Dollar

double-pane glazing for windows have evaluated in several studies [8–12]. For instance, Al-Sanea [9] and Al-Sanea and Zedan [10] has indicated that it is better to place thermal insulation on the outer surface of building envelopes to significantly reduce both peak demand and annual cooling loads for Saudi housing units. Alaidroos and Krarti [11] showed that 50-mm polystyrene insulation layer added to both the roof and walls can reduce the annual electricity consumption by 25% for a villa located in Riyadh. The effect of the window glazing type to reduce cooling thermal loads depend significantly on window-to-wall ratio and shading devices of KSA buildings [11].

Additional energy savings can incur from improved controls and operation of AC systems especially for KSA residential buildings. In particular, the impacts of cooling temperature settings as well as operation schedules of AC systems have been evaluated [5,13]. For instance, turning off AC systems when rooms are unoccupied has been estimated to save up to 45% of cooling energy end-use in a typical KSA housing unit [13]. While SEEC recommends Saudi households to set cooling temperatures at 23–25 °C [14], a survey study has indicated that most KSA houses are actually air conditioned at lower temperatures as low as 18 °C [13].

Other strategies and approaches have been proposed to reduce energy consumption associated with air conditioning of KSA residential buildings. Among the evaluated strategies include cool roofs [15], passive cooling systems such as earth tube heat exchangers and evaporative cooling systems [16–19], and high-efficiency AC equipment designs [20]. In particular, Al-Shalaan [20] has suggested some design options to improve the energy efficiency performance of room air conditioners manufactured locally in KSA. In particular, he recommended that additional of 2–3 rows of tubes for condenser and evaporator heat exchangers can increase the EER of air conditioners by at least 7%.

The benefits and cost-effectiveness of large-scale programs to improve EER of AC stock for KSA have been evaluated by limited studies using simplified analyses. Specifically, Al-Mokeheimer [21] analyzed the economic and environmental impacts of improving MEPS requirements of AC systems serving KSA villas. In particular, the study found that improving the rated energy efficiency for all the existing AC systems so their EER becomes 13.0 would result in annual savings of 24.9 TWh of electricity consumption and 15.1 Million-Ton of CO_2 emissions. A recent study by Al-Musa [22] evaluated the benefits and the cost-effectiveness of a program to replace, over an 8-year period (i.e., 2018–2025), 25% of 2016 existing AC stock with energy efficient units to reach gradually by 2022 EER = 11.8 for window ACs and EER = 14.5 for split units. The study indicated that 17.1 TWh of electricity consumption and 7.5 Million-Ton of CO_2 emissions can be saved by the end of the implementation period. The program was found highly cost-effective since it can has a present net value of 13.6 USD Million even if the government provides 100% of the capital costs needed for the program (i.e., replacement costs of the AC units). Both studies consider simplified analysis approaches based on assumptions of the AC capacities and AC operation hours without evaluating the impact of various housing types and climate conditions.

Unlike most countries, KSA still relies on window ACs to meet the increasing cooling demands especially in the housing sector. The window AC systems are energy inefficient and have lower EER values compared to other AC units such as split systems and heat pumps. Moreover, MEPS requirements for window ACs manufactured and sold within KSA have been relaxed and lagged those for split units during the last several years [4]. For example, in 2011 the minimum standard EER required was the same for both window and split systems at 7.5. However, these minimal EER requirements for split systems had risen by 2018 to 11.8 but only to 9.8 for window units. Window AC units are inherently less efficient compared to split systems due to all components being located in one single unit. One reason suggested for this differential treatment is that high EER units and replacement of Freon 22 refrigerant would affect local production of window AC units. Therefore, lower standards for window AC units have been given to allow Saudi Arabian manufacturers time to change production to adjust to higher efficiency and environmental standards. While Freon R22 is banned under the Montreal Protocol, an exemption through 2023 has been given to KSA in order to give local manufacturers time to adjust [23–25].

Detailed cost benefit analyses for improving the energy efficiency levels of AC stocks have been reported for several regions and countries including for Europe [25], Malaysia [26,27], Indonesia [28], Mexico [29], and China [30,31]. No such comprehensive analyses have been performed on the impacts of energy efficiency improvements of AC stocks in KSA. The study outlined in this paper utilizes a validated detailed bottom-up approach of the KSA residential building stock to determine the cost benefits of various retrofit programs to improve the energy efficiency performance of air conditioning equipment commonly used in KSA residential buildings. Specifically, the analysis relies on detailed hourly simulation energy modeling of 54 prototypes of KSA housing units to evaluate the energy and environmental impacts as well as the cost benefits of various programs targeted to increase the rated Energy Efficiency Ratio (EER) for both windows ACs and split units used by KSA households to maintain thermal comfort during the summer seasons. First, the analysis methodology considered in this study is described including an overview of the residential building stock model. Then, the type, the number, and the typical costs of existing AC stock in KSA are provided. Finally, the analysis results are summarized with assessments of the energy, economic, and environmental benefits as well as the cost requirements for the retrofit programs designed to enhance the energy efficiency performance of existing AC systems used in KSA residential buildings.

2. Analysis methodology

The impact of replacing the AC systems for all or part of the existing KSA housing units is evaluated using the KSA residential building stock model developed by Krarti et al. [7]. The building stock model has 54 representative housing units accounting for their types, vintages, and locations:

(i) The housing types including villas, apartment units, and traditional houses. The main features for the KSA housing prototypes are summarized in Table 1. Rendering for the energy models for the prototypes are illustrated in Fig. 1.

(ii) The vintages of the housing units are selected by their construction date and include: new (N) construction (typically less than 5 years with wall as well as roof insulation in addition to double glazing windows), recently (R) built housing (ranging from 5 years to 10 years old buildings and include only thermal insulation in walls and roof) and old (O) buildings (i.e., constructed

Table 1
Building construction specifications for three KSA prototypical housing units.

Building Model	Villa	Apartment Unit	Traditional House
Number of Floors	2	3	2
Total Floor Area	525 m^2	1260 m^2	232 m^2
Wall Construction	20 mm plaster outside +150 mm concrete hollow block +20 mm plaster inside		
Roof Construction	10 mm built-up roofing +200 mm concrete roof slab +13 mm plaster inside		
Floor Construction	Ceramic title +100 mm concrete slab on grade		
Glazing	Single-Clear with Wood Frames		
Window-to-Wall Ratio	13%	15%	15%
Infiltration	0.8 ACH	0.8 ACH	0.8 ACH
Cooling Set Point	23 °C	24 °C	24 °C
HVAC System	Split DX	AC Window	AC Window
EER	7.5	8.5	8.5
Occupancy Period	24-h/day	24-h/day	24-h/day

more than 10 years with no thermal insulation and with single glazed windows).

(iii) Six KSA locations are considered to account for both for the climatic condition and administrative regions and include Jeddah, Riyadh, Dhahran, Abha, Gizan, and Tabuk.

The stock model has been calibrated and validated using 2018 electricity consumption for the residential building sector in KSA. In particular, the EER values for the baseline energy models specific to the 54 housing prototypes are estimated through the calibration analysis as indicated in Table 2 [7]. Specifically, the building stock model has been validated using actual 2018 energy data reported for the entire housing stocks for four KSA regions as well as the entire country [32]. Table 3 compares the predictions from the building stock model to reported actual annual electricity consumptions for various KSA regions. As indicated in Table 3, the building stock model is in agreement with the actual data within less than 2% for all KSA regions [7].

The residential building stock model has been used to determine the energy end-use distribution of the KSA housing stock as summarized in Fig. 2. During 2018, the Saudi residential buildings consumed 130 TWh of electricity with air conditioning responsible for 66% of the total electricity demand.

The analysis used in this study is based on the bottom-up approach based on a building stock model coupled with the use of a detailed whole-building simulation tool to determine hourly energy use for each of the 54 housing prototypes. Specifically, DOE-2.2 simulation engine is used to determine the impact of replacing any AC unit for each of the 54 energy models on the hourly, monthly, and annual electricity use of any housing type, vintage, and location [33]. In this study, the effects of EER ratings associated to various AC systems are first evaluated on annual energy consumption and peak electrical demand for each housing prototype. Then, the energy and environments impacts of specific AC replacement programs are estimated using the bottom-up approach combined with the KSA residential building stock model as described in Ref. [7]. Finally, the implementation costs and the cost-effectiveness of

Table 2
Baseline EER for various housing prototypes set for the KSA residential building stock.

Location	Traditional Houses and Floors in Traditional Houses			Villas and Top Floors in Villas			Apartments and Others		
	O	R	N	O	R	N	O	R	N
Riyadh	8.5	8.5	9.0	8.5	8.5	9.0	8.5	8.5	9.0
Dhahran	7.5	8.5	9.0	7.5	8.5	9.0	7.5	8.5	9.0
Jeddah	8.5	8.5	9.0	8.5	8.5	9.0	8.5	8.5	9.0
Abha	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Tabuk	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Jazan	8.5	8.5	8.5	8.5	8.5	9.0	8.5	8.5	9.0

Table 3
Difference between building energy stock model predictions and reported actual data for total energy consumption for residential buildings during 2018 in four KSA regions.

Region	Actual Data (TWh/year)	Stock Model (TWh/year)	Difference
Middle	43.0	43.8	−1.7%
East	25.2	25.0	0.9%
West	45.9	45.7	0.4%
South	15.9	16.0	−0.7%
Total	130.0	130.4	−0.3%

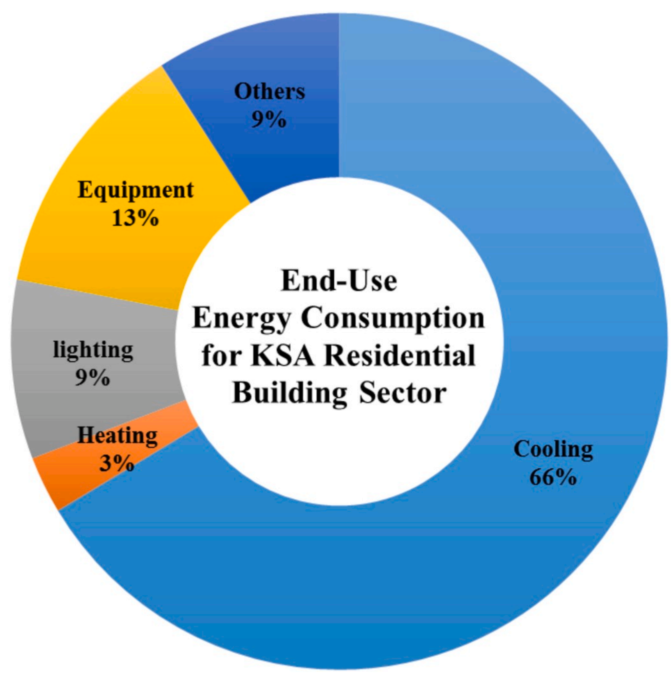


Fig. 2. Distribution of KSA residential sector energy consumption by end-use.

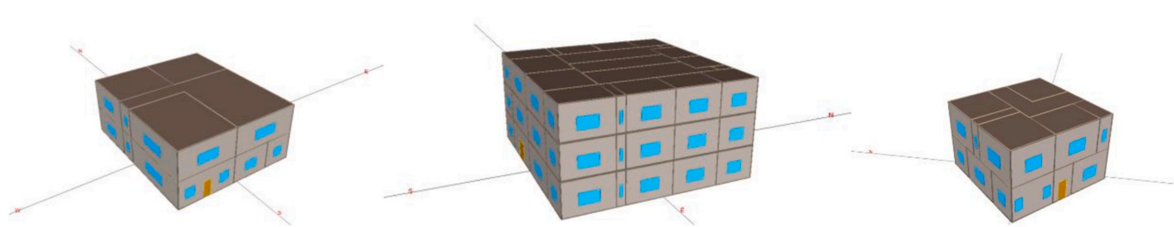


Fig. 1. Renderings of energy models for (a) villa, (b) apartment, and (c) traditional house.

these programs are determined based on AC equipment sale prices and currently available government incentives.

3. Description of current AC equipment

3.1. Existing AC stock statistics

According to the Japan Refrigeration and Air Conditioning Industry Association [34], Saudi Arabia is characterized as having the second highest sales by volume of window units for room ACs after the United States with 772,000 window units sold in KSA during 2018 representing 63% of all room AC units sold nationally as illustrated in Fig. 3. The top 10 consumers of window AC units represent 76% of the global market with the majority of countries in the world have banned or phased out most types of window units.

The type and the number of air conditioning systems utilized in the existing KSA housing stock are shown in Fig. 4 categorized by regions [35]. It is clear that Saudi residential buildings overwhelmingly use window AC units to maintain thermal comfort especially in the Western and Middle regions. Split and fan coils are the next popular air conditioning systems. Evaporative coolers and central AC systems are not commonly used in KSA. Several KSA regions are characterized by hot and dry climates and can therefore benefit from the use evaporative cooling systems as energy efficient alternatives to windows AC, fan coils, and split AC systems.

Fig. 5 shows the number of air conditioning systems per each housing unit type in all KSA provinces determined based on the 2018 survey data [35]. It is clear that households living in villas have higher number of AC units compared to those living in traditional houses followed by those residing in apartments. Indeed and for most KSA provinces, there are at least 7 AC units in villas compared to 4 AC units in traditional houses and 3 AC units in apartments. On average, each Saudi household utilizes almost 5 AC units to maintain thermal comfort within its living quarters.

Table 4 lists the specific statistics of the existing air conditioning systems used to heat and cool housing units in various KSA regions. AC windows are the prevalent systems used in all regions and represent fractions ranging from 83% (Western region) to 58% (Eastern region) of all AC systems. Split ACs represent the second dominant heating and cooling systems ranging from 39% (Eastern region) to just 14% (Western region). Evaporative coolers while suitable for dry climates such as that of Riyadh (Middle region), they only represent 2.4% of the AC stock in KSA.

3.2. Current MEPS for air conditioners

The minimum energy performance standard (MEPS) for air conditioners (ACs) have been updated several times in KSA over the last decade as summarized in Table 5 through the Saudi Arabian Standard Organization (SASO) requirements [36,37]. Specifically, SASO has set the minimum energy efficiency ratio (EER) values for ACs manufactured and sold in KSA based on two testing conditions for cooling operation mode:

- Test T1 with the outdoor conditions set to be 35 °C (95 °F) for dry-bulb temperature and 24 °C (75 °F) for wet-bulb temperature and the indoor conditions set to be 27 °C (80.5 °F) for dry-bulb temperature and 19 °C (66 °F) for wet-bulb temperature.
- Test T3 with the outdoor conditions set to be 46 °C (115 °F) for dry-bulb temperature and 24 °C (75 °F) for wet-bulb temperature and the indoor conditions set to be 29 °C (84 °F) for dry-bulb temperature and 19 °C (66 °F) for wet-bulb temperature.

3.3. Program for High Efficiency Air Conditioners

KSA has launched since 2019 the High Efficiency AC or HEAC initiative with two main goals (i) encourage local production of high energy efficiency AC systems and (ii) motivate Saudi households to purchase high performance AC systems [38]. Selected AC systems, listed in Table 6, are sold to eligible households with 900 SAR (240 USD) discount per unit.

The average costs for high efficiency AC units without the incentive are 2805 SAR (748 USD) for 1.5-ton units and 3453 SAR (921 USD) for 2.0-ton units. The program incentive is set at 900 SAR (240 USD) per unit regardless of the capacity and the manufacturer. Thus, the net average costs for the households after the application of the incentive become 1905 SAR (508 USD) for 1.5-ton units and 2553 SAR (681 USD) for 2.0-ton units. Appendices A and B list typical prices for standard AC systems including AC windows and split units that meet current MEPS.

4. Discussion of analysis results

In this section, select analysis results are presented to provide insights on the economic and environmental benefits of improving AC energy efficiency ratings including reduction of electricity peak demand as well as annual energy consumption for various KSA housing types and climatic conditions.

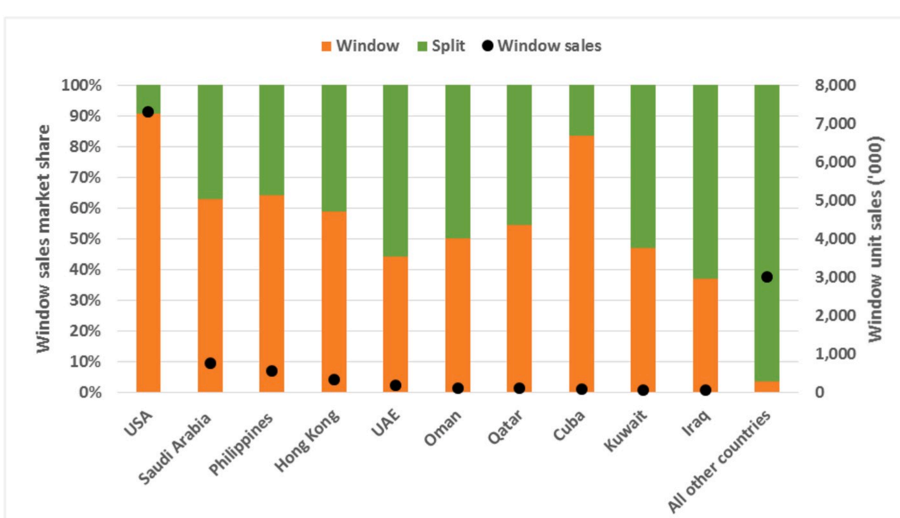


Fig. 3. Global market share and sales of window versus split systems for room AC demand Source: JRAIA [34].

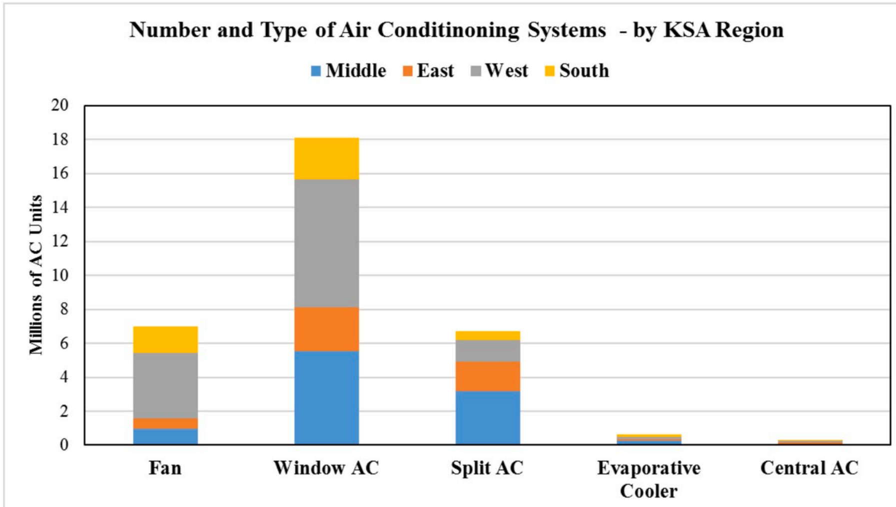


Fig. 4. Number and type of AC systems used in all housing units by KSA region.

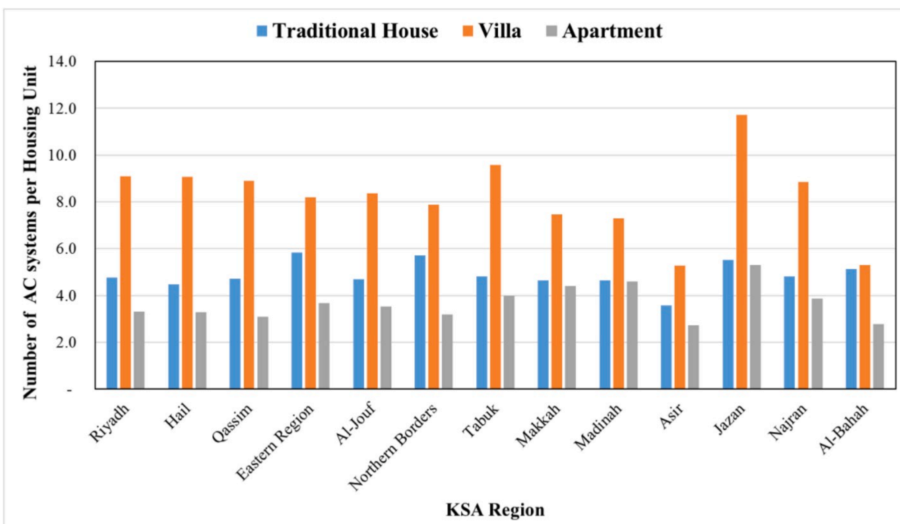


Fig. 5. Number of AC systems per housing type in all KSA provinces.

Table 4
Number of air conditioning systems for various KSA regions.

Region	Window AC	Split	Evaporative Cooler	Central AC	Total
Middle	5527779	3156779	273258	89202	9047018
East	2600922	1740311	58105	97383	4496721
West	7526368	1310262	181231	53790	9071651
South	2440921	492731	99512	9047	3042211
KSA	18095990	6700083	612106	249422	25657601

Table 5
SASO 2663 requirements for window and split ACs in KSA.

Type of Air Conditioner	Cooling Capacity (CC) at T1 conditions in Btu/hr	September 7, 2013		January 1, 2015		January 1, 2018	
		EER at T1	EER at T3	EER at T1	EER at T3	EER at T1	EER at T3
Window AC	CC ≤ 18,000	8.5	6.12	9.8	7.06	9.8	7.0
	18,000 < CC ≤ 24,000	8.5	6.12	9.7	6.98	9.8	7.0
	24,000 < CC ≤ 65,000	8.5	6.12	8.5	6.12	9.0	6.2
Split AC	CC ≤ 65,000	9.5	6.84	11.5	8.28	11.8	8.30

4.1. Impact of AC MEPS for individual housing units

Fig. 6 illustrates the potential annual energy savings of using AC systems with different EER ratings in various villa vintages located in three KSA cities. The energy savings are expressed in percentage relative to the baseline conditions as noted in Tables 1 and 2 As expected, the annual energy savings increase with the EER rating improvement and are higher for older than for newer villa vintages. It should be noted that for low EER ratings, the energy savings are negative since the baseline EER ratings are higher as summarized in Table 2. Fig. 6 indicates also that for a given EER rating, the energy savings are typically significantly higher for hot climates such as those of Riyadh and Dhahran than for colder climates such as that of Abha. For instance, the use of AC equipment of EER = 13 rating would achieve annual energy savings of 24%, 29%, and 14% for an older villa located in respectively, Riyadh, Dhahran, and Abha. For newly constructed villas, EER = 13 rated AC systems result in 18%, 23%, and 14% annual energy savings for

Table 6
List of AC models and their costs with and without the incentive.

Manufacturer/ Product	Cooling Capacity	Cooling/ Heating Options	EER	Current Cost	Cost w/o incentive
ZAMIL/ MAZ18CCXAD	1.5	C	13.1	1594 SAR	2494 SAR
ZAMIL/ MIZ18EHIAY3	1.5	C/H	13.2	2040 SAR	2940 SAR
ZAMIL/ MAZ26CCXAD	2.0	C	13.1	2198 SAR	3098 SAR
ZAMIL/ MIZ26EHIAY3	2.0	C/H	13.1	2775 SAR	3675 SAR
LG/NC182C3 SK0	1.5	C	13.1	2354 SAR	3254 SAR
LG/NC182H3 SK0	1.5	C/H	13.1	2564 SAR	3464 SAR
LG NC242C3 SL0	2.0	C	13.1	2999 SAR	3899 SAR
CARRIER/ 38SKC18US31	1.5	C	13.0	1799 SAR	2699 SAR
CARRIER/ 38SKC24US31	2.0	C	13.0	2599 SAR	3499 SAR
GIBSON/ AS120FE6IN/	1.5	C	13.1	1699 SAR	2599 SAR
GIBSON/ AS120FE7IN	1.5	C/H	13.1	1799 SAR	2699 SAR
GIBSON/ AS125FE6IN	2.0	C	13.1	2450 SAR	3350 SAR
CRAFFT/ DS120FE6IN	1.5	C	13.1	1599 SAR	2499 SAR
CRAFFT/ DS120FE7IN	1.5	C/H	13.1	1699 SAR	2599 SAR
CRAFFT/ DS125FE6IN	2.0	C	13.1	2299 SAR	3199 SAR

respectively, Riyadh, Dhahran, and Abha.

4.2. Impact of AC efficiency ratings

Fig. 7 shows the savings in total energy consumption specific to various AC EER ratings when applied to the entire KSA residential building stock accounting for various regions and housing types. The results of Fig. 7 confirm that replacing existing AC units with high-energy efficiency systems has a significant impact in reducing the overall energy consumption for the KSA residential building stock. As expected replacing AC units in housing units located in the middle and western regions achieve most of the potential energy savings since the majority of the population and housing units are located in these regions as noted in Fig. 7(a). Moreover, programs targeting AC replacements for villas and apartments achieve most of the energy consumption savings that other KSA housing types as indicated in Fig. 7(b).

4.3. Benefits of high efficiency AC retrofit programs

In this section, the benefits of three retrofit programs to replace existing cooling equipment with high efficiency air conditioning systems for Saudi households are evaluated and quantified. The evaluation is carried out using the bottom-up analysis approach based on the KSA residential building stock model and accounting for the number of AC systems utilized by Saudi households in various KSA regions.

4.3.1. Upgrade AC windows and split units to meet SASO ratings

Table 7 summarizes the annual energy savings that result from replacing the existing window ACs and split units to similar units that meet SASO rating requirements as listed in Table 1 (i.e., EER = 9.8 for window ACs and EER = 11.8 for Split units) for all housing units and various KSA regions. As expected, the impact of retrofitting window ACs has more impact than that of the split units due to their higher number. The retrofit program when applied to all KSA window ACs and split units can save over 18 TWh/year with most of these savings are achieved by order in the Middle, Western, and Eastern regions. Table 8 estimates the potential reduction in carbon emissions associated to the electricity use savings resulting from the AC retrofit program implemented in various KSA regions. Specifically, the AC retrofit program can reduce over 13 Million Tons of CO_2 emissions annually when fully implemented.

4.3.2. Upgrade AC windows to split units to meet SASO ratings

Table 9 indicates the annual electricity and carbon emission savings that occur when the existing window ACs are replaced by split units that meet SASO rating requirements (i.e., EER = 11.8) for all housing units located in various KSA regions. This retrofit program can save over 20 TWh/year and 14 Million Tons/year with most of these savings occurring in the Western region where the use of window AC systems is prevalent.

4.3.3. Upgrade AC windows and split units with EER = 13.0 units

Table 10 shows the annual electricity savings that occur when the existing window ACs and split units are replaced by split units with high energy efficiency ratings (i.e., EER = 13) for the housing stocks of various KSA regions. This specific retrofit program is currently applied in KSA with a monetary incentive of 900 SAR (i.e., USD) per AC unit [38]. As indicated in Table 10, this program has the potential to save over 33 TWh/year with most of these savings occurring in the Western and Middle regions. Table 11 shows the savings in carbon emissions savings associated with upgrading all the AC stock to meet EER = 13 rated performance level for various KSA regions. As noted in Table 11, the program has the potential to reduce over 33 Million Tons of CO_2 emissions annually.

Fig. 8 summarizes the annual energy savings and carbon emissions attributed to each of the three retrofit programs specific to the existing AC systems used by KSA households. As clearly shown in Fig. 8, upgrading AC systems with high efficiency units having EER of 13.0 has the highest impacts in saving both annual electricity use and carbon emissions for all Saudi regions.

5. Cost analysis of AC energy efficiency programs

The cost-effectiveness of the retrofit programs for upgrading the energy efficiency levels for the AC systems used by Saudi households is estimated using the average costs reported for both window AC and split units with various EER ratings. Table 12 provides a summary of these average costs based on various models commonly sold in KSA (refer to Appendices A and B). It should be noted that the current HEAC program provides a discount incentive of 900 SAR (i.e., 240 USD) per AC unit that has a rated EER of at least 13.0 [38]. The cost-effectiveness analysis results are expressed in terms of simple payback periods and summarized in Table 13 when the electricity prices charged to Saudi households is considered. As indicated in Table 13, the simple payback periods for the three programs vary notably depending on the KSA region. The Eastern region has the lowest payback periods for all the three programs. Moreover, the program that calls for upgrading AC systems to high energy efficiency units with EER rating of 13.0 has the lowest payback period for all the regions especially when the discount incentive is

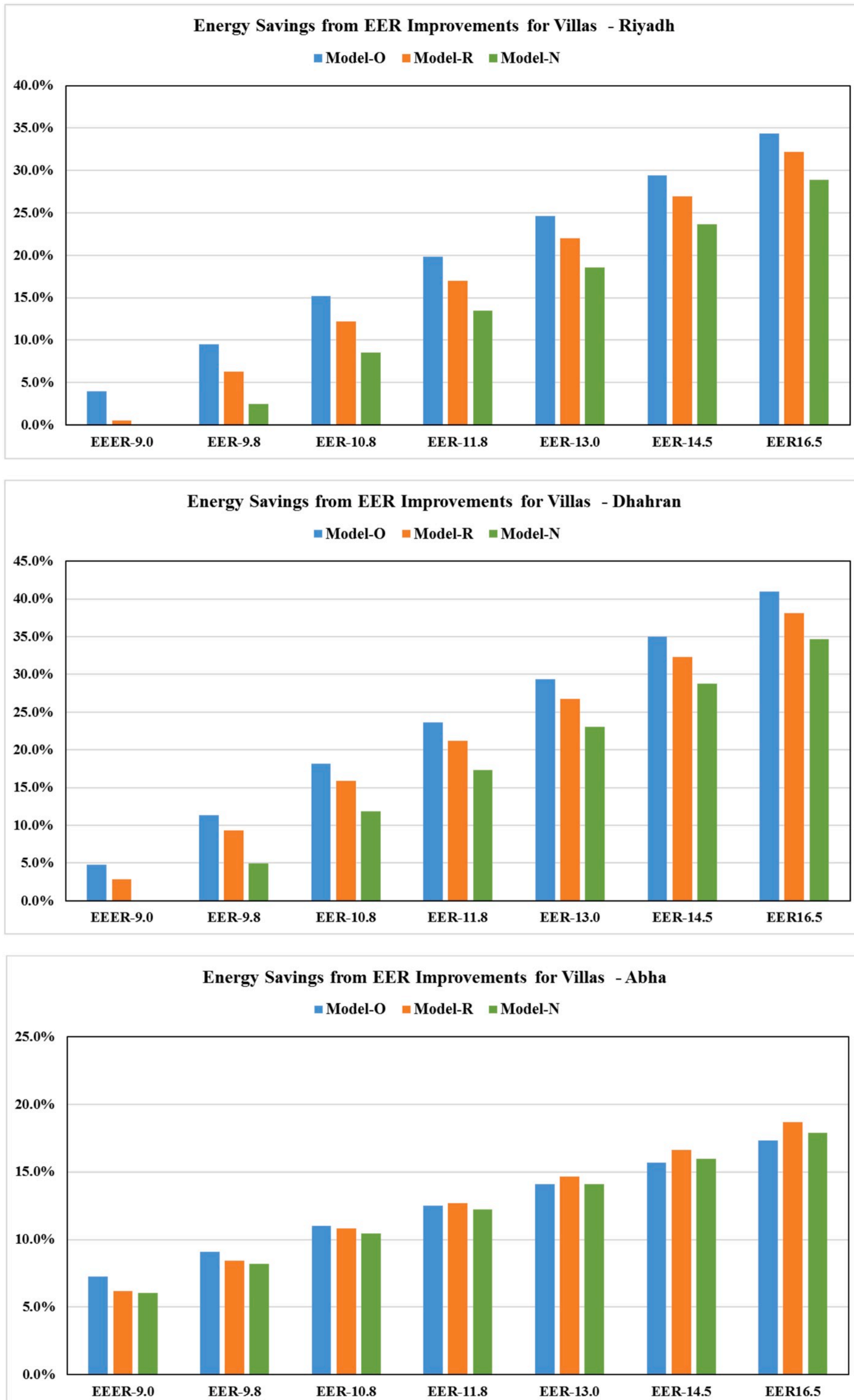
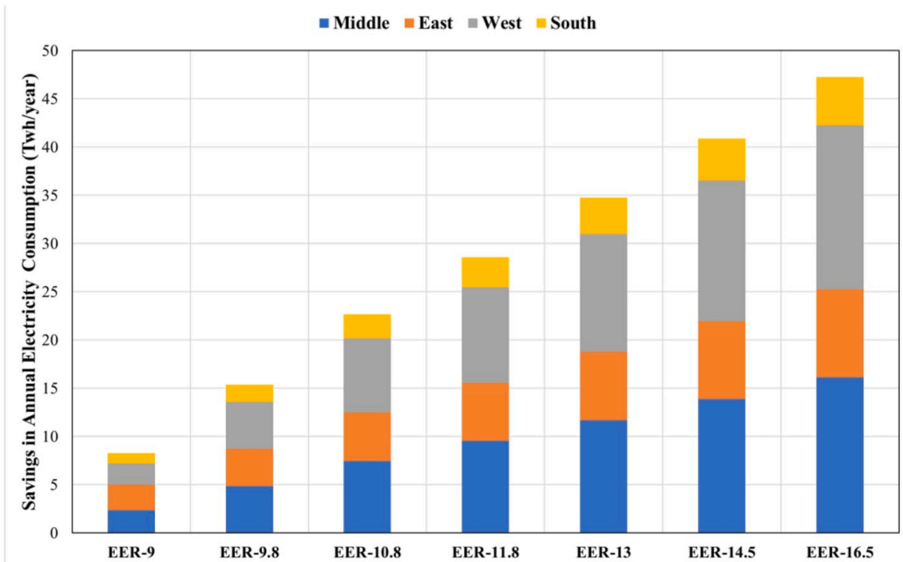
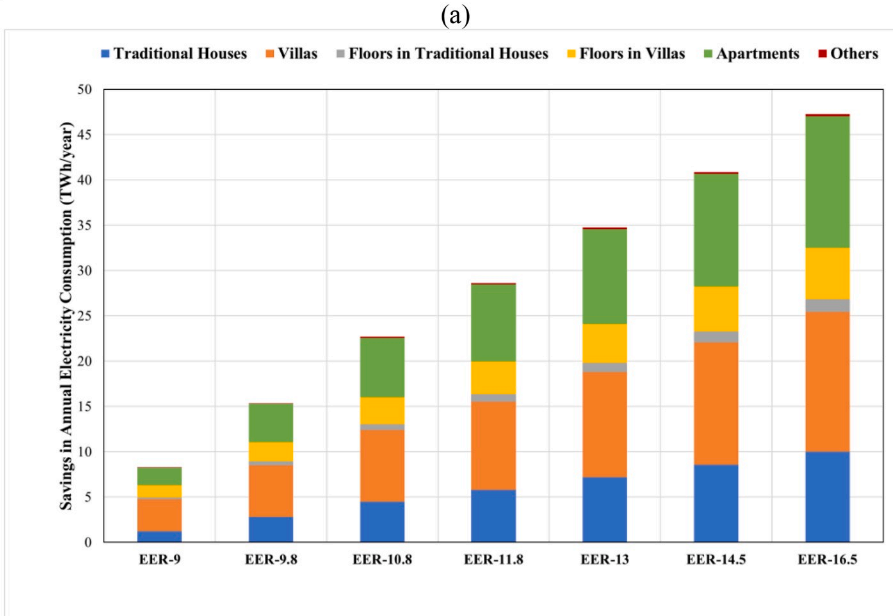


Fig. 6. Savings in annual electricity consumption for various AC efficiency ratings for three villa vintages located in three KSA cities.



(a)



(b)

Fig. 7. Savings in annual electricity consumption for various AC efficiency ratings (a) by regions and (b) housing types.

Table 7
Annual Savings in Electricity Consumption expressed in TWh/year for Upgrading of Window ACs and Split Units to meet SASO Ratings.

Action	Region				
	Middle	Eastern	Western	Southern	KSA
AC Window to 9.8	2.979	2.216	4.036	1.424	10.656
Split to 11.8	3.329	2.336	1.429	0.504	7.599
Program	6.308	4.552	5.466	1.929	18.255

Table 8
Annual Savings in Carbon Emissions expressed in Million Tons/year for Upgrading of Window ACs and Split Units to meet SASO Ratings.

Action	Region				
	Middle	Eastern	Western	Southern	KSA
AC Window to 9.8	2.127	1.582	2.882	1.017	7.609
Split to 11.8	2.377	1.668	1.021	0.360	5.425
Program	4.504	3.250	3.903	1.377	13.034

applied. Indeed, with the discount of 900 SAR (i.e., 240 USD), the simple payback period for upgrading the existing AC systems to units of EER = 13.0 ranges from 4.6 years for the Eastern region to 5.9 years for the Southern region.

When considering the KSA government perspective, the rebate of 900 SAR (i.e., 240 USD) would amount to an investment of 5.95 USD Billion if all the existing residential AC units were replaced as depicted in Table 14 for the regional analysis. The avoided fuel consumption results in an annual income of 3.0 USD Billion from sales using international market prices instead of the preferential prices to Saudi electricity produces as noted in Table 14. For the KSA government, the rebate program has a simple payback period of just 2.0 years. The additional benefits for the program not included in the cost analysis for the government perspective include:

(i) A reduction in peak electrical demand and thus the reduction in the needs of building power plants to meet future electricity needs for the growing residential sector.
(ii) A reduction in carbon emissions as detailed in Table 10.
(iii) An increase in market potential for Saudi AC manufacturers since the improvements in the energy efficiency ratings of their systems allow them to penetrate markets in other countries when MEPS for air conditioners are more stringent in KSA.

6. Conclusions

The benefits of improving the energy efficiency of air conditioning systems sold to Saudi households have been evaluated using a bottom-up approach based a residential building stock model to account for variations in housing types, vintages, and locations. The analysis has shown that significant savings in energy consumption, peak electrical demand, and carbon emissions can incur from programs that strengthen the minimum energy performance standards for air conditioners and/or that incentive households to install high efficiency cooling systems.

Table 9
Annual Savings in Electricity Consumption expressed in TWh/year for upgrading of Window ACs to Split Unit.

Annual Savings	Region				
	Middle	Eastern	Western	Southern	KSA
Electricity Consumption (TWh/year)	5.830	3.491	8.211	2.499	20.030
Carbon Emissions (Million Tons/year)	4.162	2.492	5.863	1.784	14.301

Table 10
Annual Savings in Electricity Consumption expressed in TWh/year for upgrading of Window ACs and Split Units to meet EER = 13 requirements.

Action	Region				
	Middle	Eastern	Western	Southern	KSA
AC Window to 13.0	7.153	4.082	10.149	2.997	24.382
Split Units to 13.0	4.085	2.732	1.767	0.605	9.188
Program	11.238	6.814	11.916	3.603	33.570

Table 11
Annual Savings in carbon emissions expressed in Million Tons/year for upgrading of Window ACs and Split Units to meet EER = 13 requirements.

Action	Region				
	Middle	Eastern	Western	Southern	KSA
AC Window to 13.0	5.107	2.915	7.246	2.140	17.409
Split Units to 13.0	2.917	1.950	1.262	0.432	6.560
Program	8.024	4.865	8.508	2.572	23.969

Specifically, three large-scale programs have been considered for improving the energy efficiency ratings of existing air conditioners in the Kingdom of Saudi Arabia:

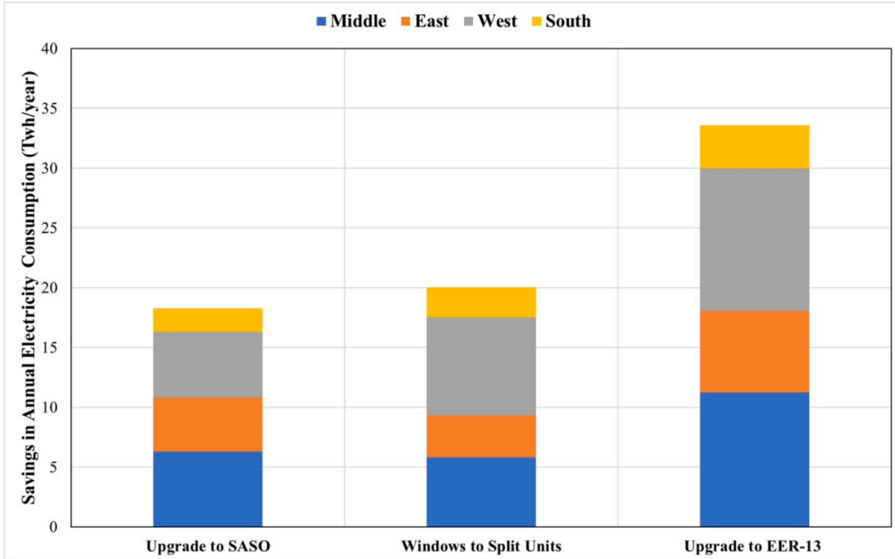
(i) Enforce that all the existing air conditioners meet current MEPS requirements. This program entails that old air conditioners are replaced with new systems that meet the energy efficiency ratio (i.e., EER) ratings of 9.8 for window units and 11.8 for split units. This program results in annual savings of 18.3 TWh of electricity consumption and 13.0 Million-Ton of carbon emissions.
(ii) Make the MEPS requirements for EER ratings more stringent for window units or replace these units with split units so that their minimum EER is 11.8. The annual savings for this program are 20.0 TWh of electricity demand and 14.3 Million-Ton of carbon emissions.
(iii) Incentive all Saudi households to replace their air conditioners with systems that have a minimum EER rating of 13.0 as currently proposed by the High Efficiency Air Conditioners (HEAC) initiative. If fully implemented, the program can achieve annual reductions of 33.6 TWh of electricity use and 24.0 Million-Ton of carbon emissions.

For a typical household, the best option would be to replace their AC systems with high efficiency split units (EER = 13.0) through the HEAC initiative that provides a rebate of 900 SAR (240 USD) per AC unit. Indeed, the HEAC results in lower simple payback periods for typical Saudi households ranging from 4.6 to 5.7 years depending on the KSA region. While oil prices have recently fallen due to the global collapse in oil demand due to the corona virus, the Saudi government can recover the funds specific to the HEAC initiative in just 2 years given the domestic oil price paid by utilities is around 6 USD/barrel versus possible international prices of 60 USD/barrel.

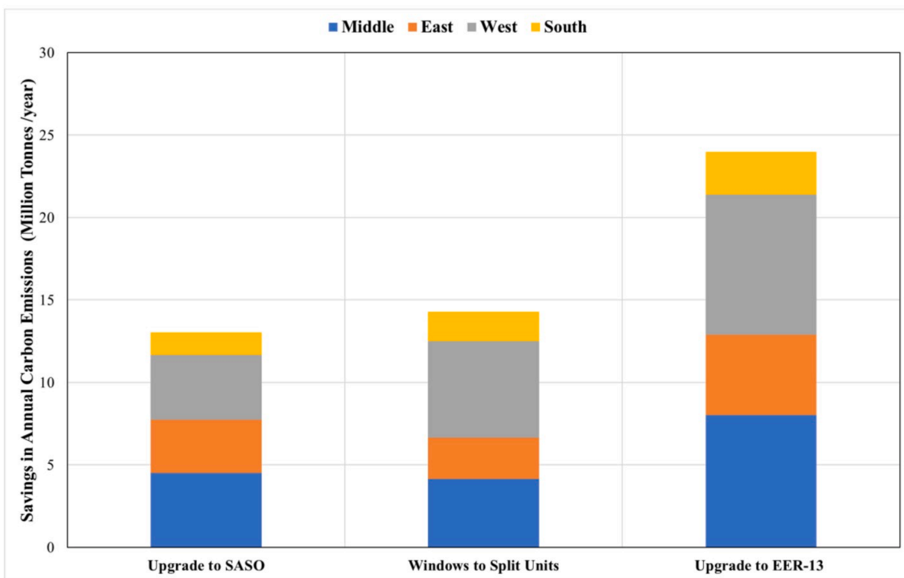
The analysis outlined in this study clearly indicates that Saudi households and ultimately KSA government should scale up its high-energy efficiency air conditioning programs. The voluntary approach of the HEAC program can be enhanced through more structured policies such as strengthening MEPS and refrigerant requirements to effectively phase out window units and increase the efficiency of split systems to the minimum standard required for the HEAC program.

CRediT authorship contribution statement

M. Krarti: Investigation, Data curation, Software, Methodology, Validation, Writing - original draft. **Nicholas Howarth:** Conceptualization, Writing - review & editing.



(a)



(b)

Fig. 8. Savings in annual (a) electricity consumption and (b) carbon emissions for three AC retrofit programs in KSA regions.

Table 12
Average costs per unit of AC systems sold in KSA expressed in SAR and USD.

AC Type	Standard AC Window	Standard Split AC	Efficient Split AC	Efficient Split AC with Discount
Energy Efficiency Ratio or EER	9.8	11.8	13	13
Average Cost in SAR	1627	2698	3064	2164
Average Cost in USD	434	719	817	577

Table 13
Payback period expressed in years for energy efficiency upgrade programs for existing window ACs and split units in KSA.

Action	Region				
	Middle	Eastern	Western	Southern	KSA
Upgrade to SASO requirements	9.3	6.5	9.6	9.2	8.7
Window ACs to Split Units	8.5	6.7	8.2	8.8	8.1
Upgrade to EER = 13 units (with 900 SAR incentive)	5.6	4.6	5.3	5.9	5.3
Upgrade to EER = 13 units (without any incentive)	7.9	6.5	7.6	8.3	7.5

Table 14
Cost benefits for the KSA government for the incentive program to upgrade existing residential AC units with energy efficient systems (i.e., EER = 13).

Action	Region				
	Middle	Eastern	Western	Southern	KSA
Cost of the Incentive Program (Billion USD)	2.08	1.04	2.12	0.70	5.95
Annual Fuel Savings[a] (Million of BOE/year)	18.58	11.26	19.70	5.95	55.49
Annual Income from Fuel Sales[b] (Million USD/ year)	1.00	0.61	1.06	0.32	3.00
Simple Payback Period (Years)	2.08	1.71	1.99	2.19	1.99

[a] Electricity generation average efficiency of 35.6% is used [39].
[b] The income is estimated from the difference in crude oil price between the international market (60 USD per barrel) and the preferential rate to KSA electricity producers (reported to be 5.94 USD per barrel [40]).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101457.

Appendices.

A- Prices for Split ACs

Table A1
List of Standard Efficiency (EER = 11.8) AC models for Split Systems

Manufacturer/Product	Cooling Capacity (Ton)	Cooling/Heating Options	Current Cost	Cost w/o discount
GREE/GWH18QE- S3DTB4	1.5	C/H	2599 SAR	3849 SAR
GREE/GWC24AC-D3NTA1	2.0	C	2599 SAR	3899 SAR
LG/NP182HSK1	1.5	C/H	2299 SAR	3469 SAR
LG/NS242CSK0	2.0	C	3549 SAR	3675 SAR
YORK/YHFE18XT3BFE	1.5	C	2099 SAR	2399 SAR
YORK/YHGE24XT2BFE-R3	1.9	C/H	3109 SAR	3109 SAR
HAIER/HSU-24LZE13	2.0	C	2629 SAR	2629 SAR

B- Prices for Window ACs

Table B1
List of Standard Efficiency (EER = 9.8) AC models for Window Systems

Manufacturer/Product	Cooling Capacity (Ton)	Cooling/Heating Options	Current Cost	Cost w/o discount
GREE/GJC18AG-D3NMTD5A/D	1.5	C	1149 SAR	1289 SAR
GREE/GJC24AE-D3MTD5A	2.0	C	1469 SAR	1599 SAR
LG/D182ECSN2	1.5	C/H	1399 SAR	1729 SAR
LG/E242RHSN2	1.7	C/H	1499 SAR	2499 SAR
GENERAL XSS24FHTC/	2.0	C	2229 SAR	2899 SAR
GENRAL/AXSS18FHTA	1.5	C	2019 SAR	2299 SAR

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